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INTEGRATED, BISTABLE GAIN- QUENCHED VERTICAL CAVITY/IN-PLANE LASERS FOR SMART PIXEL SWITCHING, FREE-SPACE INTERCONNECTS, AND OPTICAL MEMORY APPLICATIONS

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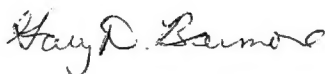
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Executive Summary

We report new experimental results demonstrating optical bistability and two-input NOR gate operation in intracavity-coupled in-plane and vertical cavity surface emitting lasers (VCSELs) fabricated from the same epitaxial material. The VCSEL (or output) section gain is controlled by separately biased in-plane laser section(s), and depending on the in-plane power output, complete quenching of stimulated emission in the VCSEL is observed. Hysteresis is present in the VCSEL output power versus in-plane laser input power characteristic, and an optical memory effect is observed in the combined device.

We also report the experimental demonstration of monolithic all-optical 1:N routing switches using CW gain-quenched, intracavity-coupled in-plane and vertical cavity surface emitting lasers (VCSELs) as the switching elements. These optically-coupled laser devices are capable of time-division multiplexing and demultiplexing operations, and the VCSEL sections may also be used as electrically- or optically-controllable large-aperture output couplers for in-plane laser modulation signals. The routing switch outputs have an on/off contrast ratio of >20 dB, and negligible crosstalk between channels. These devices will have a wide variety of applications, including logic gates and buffers in optical switching networks.

I. Multiple-Input Optical Control Of Vertical Cavity Surface Emitting Lasers Using Intracavity-Coupled In-Plane Lasers

A. Introduction

A variety of potential applications of semiconductor lasers depend on multiple-input control of the laser characteristics. These include all-optical logic, memory, and time-, space-, or wavelength-division switching operations. In the case of in-plane lasers (IPLs), control can be achieved through a variety of intracavity elements and modulation techniques. By contrast, the short cavity length of typical stand-alone vertical cavity surface emitting lasers (VCSELs) makes it difficult to implement analogous multiple-input electrical intracavity-modulation schemes. Conventional VCSEL output is normally determined by direct electrical-current control of the gain of the laser medium. However, multiple-input control of the VCSEL gain can be achieved through intracavity-coupled in-plane lasers. Added benefits are the ease of signal transfer out of the plane of the wafer, and inversion of input signals to the in-plane laser section.

Gain-controlled, intracavity-coupled in-plane lasers and VCSELs fabricated from the same epitaxial material have recently been reported [2]. The mechanism by which gain quenching and two-mode bistability occur is through mode-competition in the gain region common to both lasers. Once one laser is lasing, the gain for the other laser is reduced and the corresponding threshold for oscillation increases accordingly. This leads to a hysteresis effect or bistability. While cross-coupled in-plane lasers have used saturable absorber sections to obtain bistability [6-9], in this work the common gain region is the VCSEL section itself. It has been pointed out that the conditions for bistability in cross coupled lasers depend on the individual lasers' self- and cross-saturation coefficients, and that the cross-saturation terms are highest when their gain section overlap is maximized [4-5]. Consequently, the hysteresis in the power output vs. power input characteristic of cross-coupled VCSELs and in-plane lasers is expected to be larger and more easily

realized than that observed in cross-coupled in-plane lasers alone, owing to the complete cavity overlap in this case. We report in this letter the first observation of optical bistability in cross-coupled VCSELs and in-plane lasers, and we present a two-input NOR gate which demonstrates the flexibility of this switching technology.

B. Experimental Results and Discussion

A conceptual sketch of a $20\text{ }\mu\text{m}^2$ VCSEL intracavity-coupled to two orthogonal $20\times 400\text{ }\mu\text{m}$ in-plane lasers A and B is shown in Figure 1. The fabrication of these devices has been described in detail previously [2]. The VCSEL DBR mirrors consisted of a 19-pair $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}/\text{AlAs}$ top stack and a 29-pair bottom stack of the same composition, with graded interface layers. The IPL sections employed these stacks as cladding layers, and the active region consisted of three $80\text{ }\text{\AA}$ GaAs quantum wells. The operating wavelength of both the VCSELs and the in-plane lasers was approximately 847 nm , and the threshold levels were quite high; the IPLs lased at $\sim 700\text{ A/cm}^2$ and 12 V , and the VCSELs at $\sim 4000\text{ A/cm}^2$ and 12 V . These values were measured with the intracavity coupled laser unbiased, and the thresholds were attributed to high series resistance due to device contact processing problems. Coupling gaps were located between the gain sections of the in-plane lasers and the VCSEL (or output) section of the NOR gate to allow each to be independently biased. The end mirrors of the integrated in-plane lasers were deep-etched by electron cyclotron resonance (ECR) etching. The shallow and deep etches are created in the same process using a one-step two-level etching technique [10-11].

Figures 2 (a)-(c) demonstrate the operation of the NOR gate. In Figure 2 (a), the lower, abrupt on/off oscilloscope trace is an untruncated $1\text{ }\mu\text{sec}$ voltage input pulse to the VCSEL, with the in-plane laser sections unbiased. The upper trace is the VCSEL output measured with a 1 cm diameter Si photodetector. In Figure 2 (b), the lower trace is a 500 nsec voltage pulse applied to in-plane laser A, and the upper trace again shows the VCSEL output, together with a small amount of scattered light from the in-plane laser. It is clearly seen that when the in-plane laser A is biased

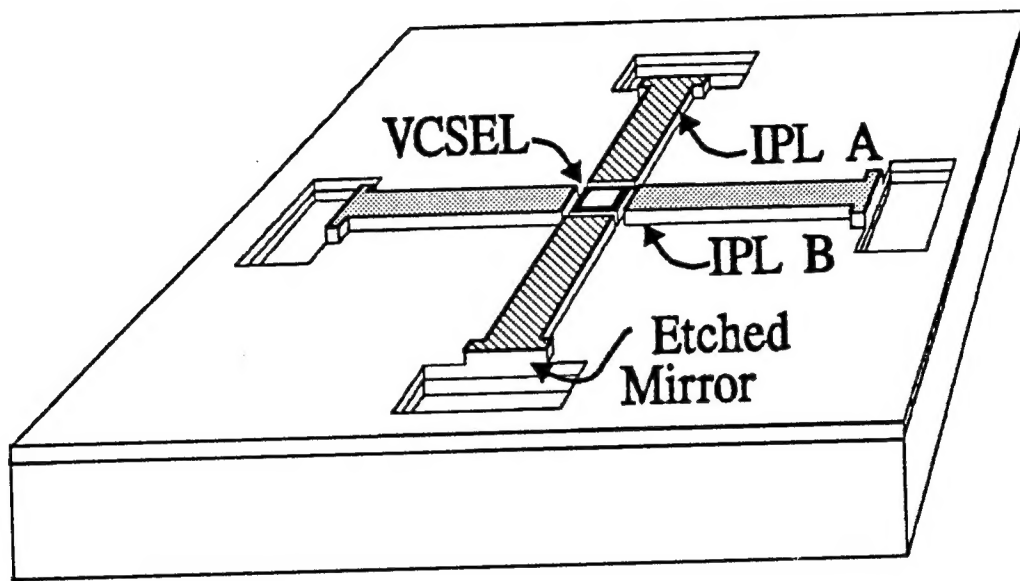


Fig. 1 Conceptual sketch of the all-optical two-input NOR gate. The end mirrors of the in-plane lasers and the coupling gaps are created by electron-cyclotron resonance etching.

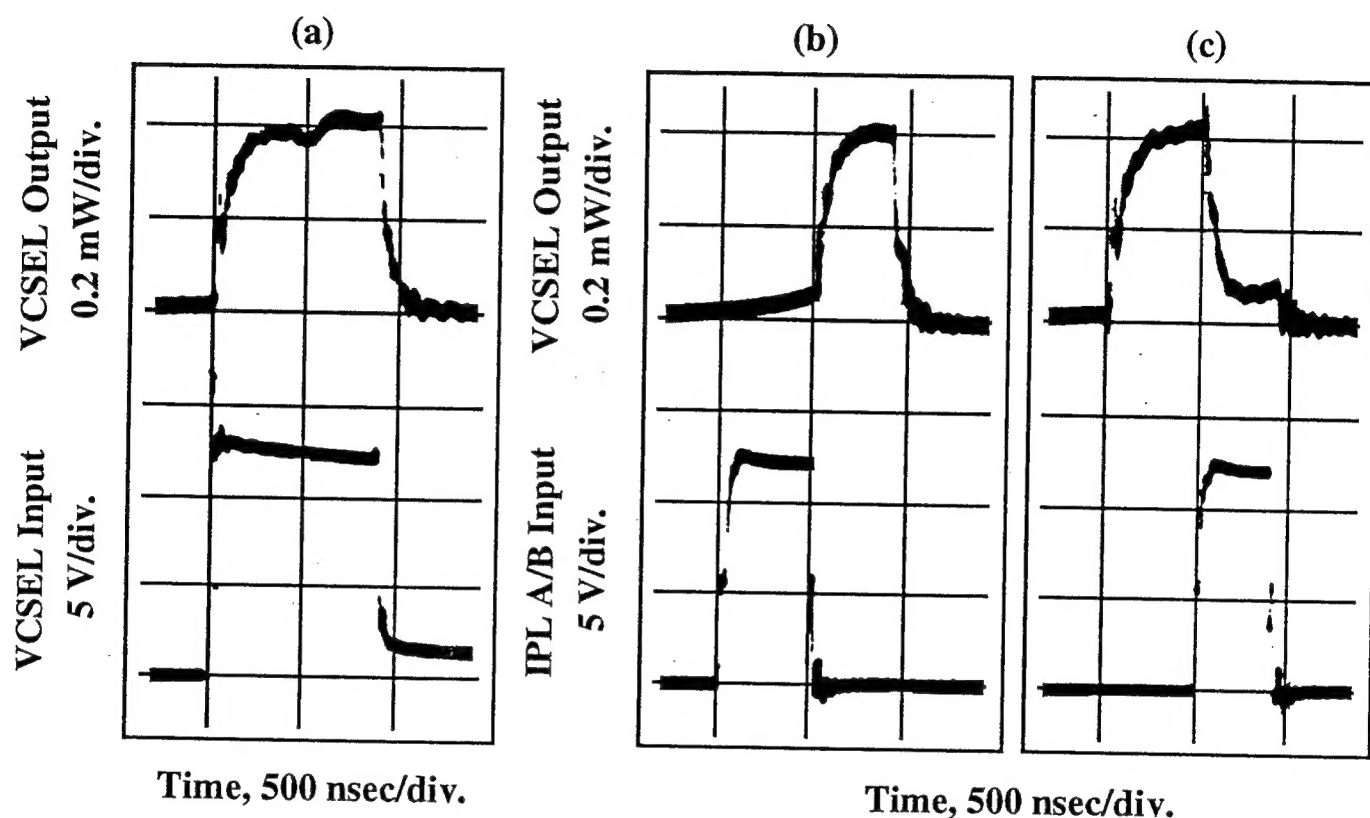


Fig. 2 Oscilloscope traces showing NOR gate operation in a $20 \mu\text{m}^2$ VCSEL integrated with and intracavity coupled to two orthogonal $20 \times 400 \mu\text{m}$ in-plane lasers A and B. (a) An untruncated $1 \mu\text{sec}$ VCSEL pulse. (b) Leading edge of VCSEL pulse truncated by a 500 nsec pulse on in-plane laser A. (c) Trailing edge of VCSEL pulse truncated by a 500 nsec pulse on in-plane laser B.

above threshold in the logic 1 state, the VCSEL output pulse is truncated (spontaneous emission only, or logic 0) until the time when the in-plane laser is turned off. At that point, the VCSEL output rises to its lasing or logic 1 output level. During this measurement, the orthogonal in-plane laser (B) is off. Figure 2 (c) shows another scenario, measured using in-plane laser B. The VCSEL is initially in its lasing or logic 1 state. At a later time, the output of in-plane laser B is raised from logic 0 to logic 1, or lasing. The VCSEL output, again shown as the upper trace, is then suppressed to the logic 0 state. The on/off contrast ratio between the logic states is at least 5:1, and varies with the timing of either IPL pulse relative to the start of the VCSEL pulse. This is because of the influence of each in-plane laser on the VCSEL's threshold current (and vice versa), depending on which laser is turned on first. This is discussed in greater detail below.

Figure 3 shows the hysteresis in the power output vs. power input characteristic of a 20 μm^2 VCSEL intracavity-coupled to a 20x600 μm in-plane laser. In the upper portion of the loop, the VCSEL is lasing, and the in-plane laser is off. As the top of the loop is traversed from left to right, the VCSEL output initially increases. Here, the spontaneous emission from the in-plane laser optically pumps the VCSEL, thereby decreasing its threshold current. Eventually, the light output of the in-plane laser increases rapidly as it begins to lase at P_1 , and the VCSEL output is suppressed to below 0.05 mW of spontaneous emission when the in-plane laser is at full output. When the in-plane laser power is reduced, the VCSEL output remains low until P_2 is reached, at which point the VCSEL begins to lase again. To ensure that the VCSEL output only was being measured, the scattered light from the in-plane laser was measured separately using the large-area detector mounted above the wafer, and then subtracted from the combined in-plane and VCSEL output signal. The in-plane output was also monitored using a vertical cavity photodetector fabricated adjacent to an end mirror and coupled through a polyimide-filled 3 μm gap. The observed hysteresis loop is approximately 20 mA wide, from inspection of the in-plane current axis of Figure 3. The clockwise nature of the loop is due to the inverting nature of the combined in-plane and VCSEL pair. Reduced output and device heating were observed when longer pulses

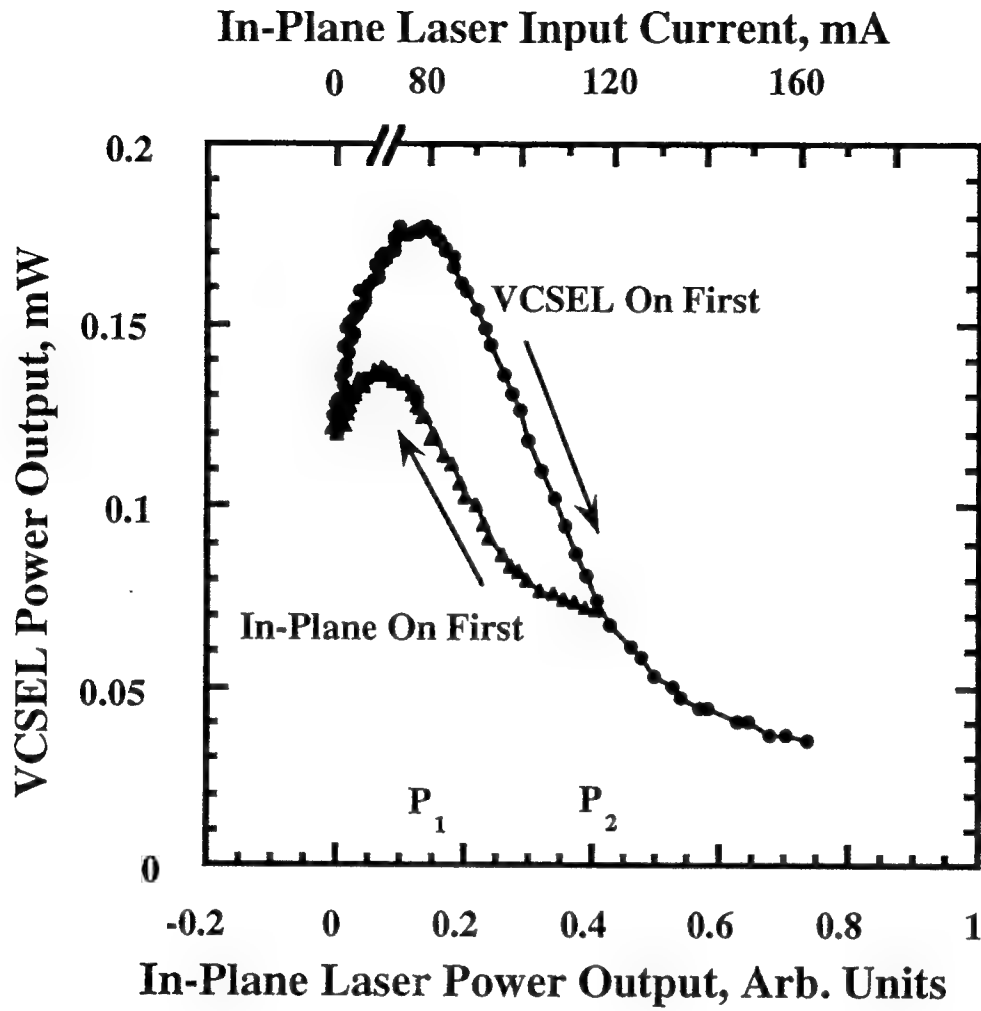


Fig. 3 Optical hysteresis in a $20 \times 600 \mu\text{m}$ in-plane laser intracavity-coupled with a $20 \mu\text{m}^2$ VCSEL. (●) VCSEL lasing first, in-plane power output increasing. (▲) In-plane laser on first, in-plane power output decreasing.

of several μsec duration were used, and consequently the pulse width for all measurements was limited to $\leq 1 \mu\text{sec}$ and the duty cycle was held constant at 0.2% to minimize these effects.

Fig. 4 demonstrates the optical bistability in a $10 \mu\text{m}^2$ VCSEL intracavity-coupled with a $10 \times 100 \mu\text{m}$ in-plane laser. The oscilloscope trace in part (a) shows a two-level pulse applied to the in-plane laser, and the VCSEL output which results. As in Fig. 3, the VCSEL bias for the duration of the IPL pulse was held constant at a level near the center of the hysteresis loop. The nominal in-plane bias level was just above the IPL threshold, and the superimposed pulse brought the IPL output to just beyond the hysteresis loop. An optical memory function is clearly seen, as the VCSEL output does not recover to the nominal level it reached during the first half of the in-plane laser pulse after the in-plane laser is returned to its nominal bias level. Presumably, this new bias condition is on the lower branch of the hysteresis loop. By contrast, a similar device measured in Figure 4 (b) does in fact show a recovery to near the nominal VCSEL output level when the in-plane laser returns to its (sub-threshold) bias point. The IPL was again biased just beyond the hysteresis loop during the superimposed pulse. The set and reset times of $\sim 150 \text{ nsec}$ are limited by the high series resistance in the devices studied, and the concomitant increase in the RC charging time constant. Future work will focus on lower resistance and CW operation.

Applications for the intracavity coupled laser pair include integrated optical logic gates and inverters, optical interconnection between signal planes with low-divergence output beams, and sources and optical memory elements for dense wavelength division multiplexed (WDM) switching networks or time slot interchange circuits. While the devices presented are optically controlled by means of an electrical input signal, an all-optical switch may also be implemented, e.g. by injecting light into the in-plane cavity to toggle the VCSEL output, or by using a separate photodetector supplying current to an intracavity modulator section in the IPL. For a routing application, an analog or digital input signal may be amplified by a main in-plane laser with multiple intracavity VCSEL sections, which may operate at different wavelengths. The time slot or the wavelength of the output signal may then be chosen by turning off the side in-plane laser coupled to the desired VCSEL section, thereby allowing that VCSEL to lase. The bistability of the coupled laser pair may

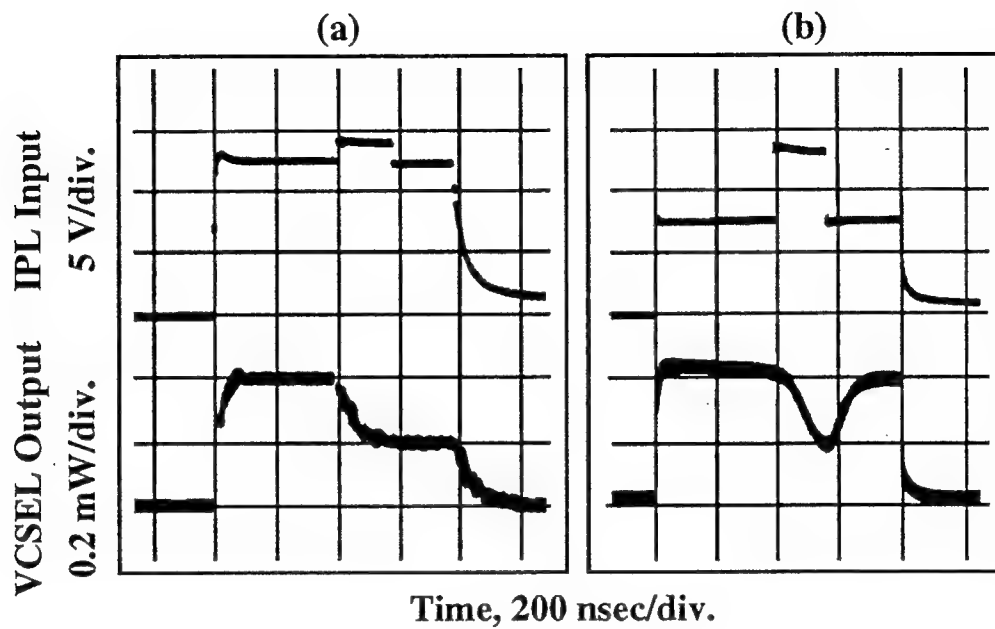


Fig. 4 Optical memory and bistability in $10\text{ }\mu\text{m}^2$ VCSELs integrated with $10\times 100\text{ }\mu\text{m}$ in-plane lasers. (a) VCSEL and in-plane laser initially biased within hysteresis loop. VCSEL output does not recover after in-plane laser returns to its nominal bias level. (b) VCSEL and in-plane laser initially biased outside hysteresis loop. VCSEL output recovers after the superimposed in-plane laser pulse.

also be used to advantage by incorporating such elements as buffers or latches for optical memory applications.

C. Conclusion

We have demonstrated optical bistability and NOR gate operation in intracavity coupled in-plane and vertical cavity lasers fabricated from the same epitaxial material. The combined device enables multiple-input intracavity control of VCSEL output, and it offers a wide variety of potential applications in integrated all-optical logic gates, memory elements, and time-, space-, or wavelength-division switches.

II. Coupled In-Plane and Vertical-Cavity Laser 1xN Routing Switches

A. Introduction

In recent years, there has been a great deal of interest in 1xN routing switches for optical network interconnections. These are commonly implemented by electrical or optical control of passive interferometers which make use of electro-optic or third-order nonlinear effects in optical materials. LiNbO₃-based devices, for example, are widely used in optoelectronic switching applications [1]. These switches are bulky, have no gain, require high voltages, and are incompatible with monolithic photonic integrated circuit (PIC) technology. In order to achieve high pixel density ($>1000/\text{cm}^2$) networks which are more easily manufactured, a need exists to develop optical routing switches which are compatible with common semiconductor laser fabrication techniques.

It has been shown previously that in-plane lasers and vertical cavity surface emitting lasers (VCSELs) fabricated in the same epitaxial material can exhibit complete gain quenching of the stimulated emission in intracavity-coupled devices [2]. Furthermore, when multiple in-plane lasers are coupled to a single output VCSEL, an all-optical NOR gate is formed. The mechanism by which this occurs is through mode competition in the gain region common to both lasers. Once the first laser is lasing, the gain for the other laser(s) is reduced, and their threshold current increases accordingly. Depending on the overlap between the lasers' cavities, optical bistability is also observed [3]-[5]. While control of in-plane laser characteristics can be achieved through a variety of intracavity elements and modulation techniques, the short cavity length of typical stand-alone VCSELs makes it difficult to implement analogous electrical intracavity-modulation schemes.

The use of intracavity saturable absorber sections to achieve gain quenching and bistability in cross-coupled in-plane lasers has been the subject of related work [6]-[9], which is necessary

for cascading such devices in a two-dimensional optical switch network. However, these approaches do not offer the advantages of an intracavity-coupled VCSEL for output coupling purposes. In this letter, we report the experimental demonstration of a new type of monolithically-integrated, all-optical 1:N routing switch using CW gain-quenched, intracavity-coupled in-plane and vertical cavity surface emitting lasers (VCSELs) as the switching elements. The combined device provides coupling directly from in-plane lasers into free-space or optical fibers, in addition to having time-division multiplexing and demultiplexing capability.

B. Experimental Results and Discussion

A functional and conceptual sketch of a coupled in-plane and vertical-cavity laser 1x3 routing switch are shown in Figure 5, together with a SEM micrograph of a completed device. The $20 \times 700 \mu\text{m}$ -long main in-plane laser has three $20 \mu\text{m}^2$ intracavity VCSEL sections for coupling out the modulation signal. Each of these VCSELs has a $20 \times 200 \mu\text{m}$ side in-plane laser associated with it, for the purpose of optically controlling its output (e.g., for time demultiplexing) or for introducing other modulation signals to the main in-plane laser. The fabrication of similar devices has been discussed in detail previously [2]. The lasers are electrically isolated from each other by shallow etching partly into the top 20-pair mirror stack, and by proton implantation. The end mirrors of the integrated in-plane lasers were deep-etched into the n-GaAs substrate using a Ni mask on top of the p-contact metallization. Cladding of the in-plane lasers is provided by the DBR mirror stacks, and the active region consisted of four 80\AA GaAs quantum wells. The individual lasers in the structure are separately biased, and are created simultaneously using a one-step two-level electron-cyclotron resonance (ECR) etching technique [10], [11].

The 1:N routing switches operate as follows. A modulation signal is introduced to the main in-plane laser, in this case by varying the drive current. In Figure 5 (c), another method of introducing this signal is shown, using a separately biased modulator section in the main laser. Other conventional techniques, such as optical injection of the modulation signal into the main laser

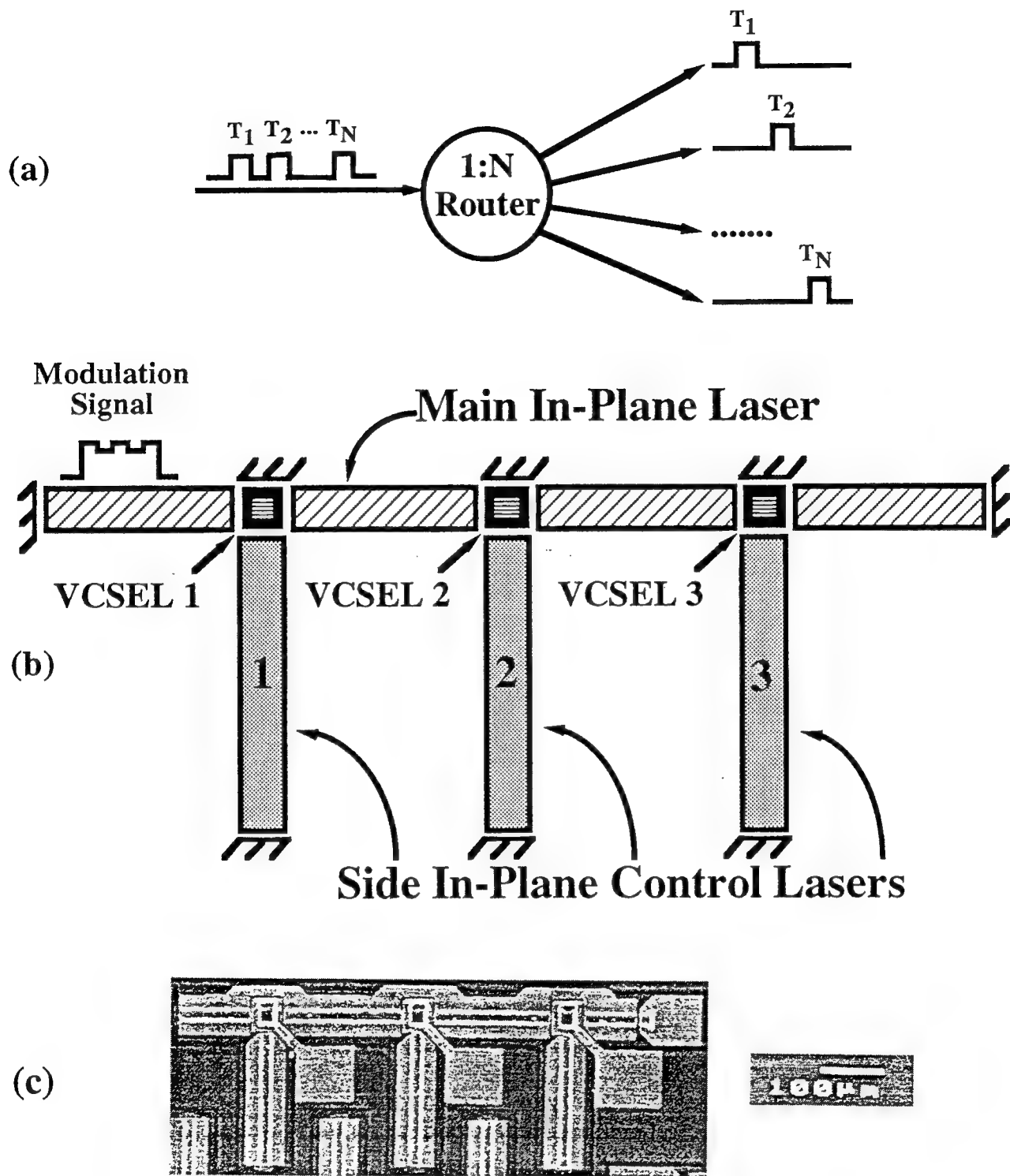


Fig. 5 (a) Functional and (b) conceptual sketch of a monolithic all-optical 1:N routing switch. (c) A SEM micrograph of a completed device. The $20 \times 700 \mu\text{m}$ main in-plane laser has three $20 \mu\text{m}^2$ intracavity-coupled VCSEL output sections, each with a $20 \times 200 \mu\text{m}$ side in-plane control laser. The extra contact pad on the right-hand side of the main laser is a separately-biased cavity section for the purpose of introducing a modulation signal.

via an external fiber or an integrated optical waveguide, may also be used. The main laser and its intracavity VCSEL sections are biased above threshold, so that the modulation signal causes the stimulated emission in the VCSELs to be switched on and off. The VCSEL outputs thus invert and amplify the main laser modulation signal in the absence of input light from their associated side in-plane control lasers. This can be seen in Figure 6, in which the side lasers are off. The 847 nm output of both VCSELs is measured with the same 1 cm^2 Si photodetector, giving rise to the superposition of the output signals in region II. The magnitude of the individual VCSEL output pulses in regions I and III were arbitrarily chosen by adjusting the VCSEL bias currents, to clarify which outputs are on at which times. An on/off contrast ratio of $>20 \text{ dB}$ is observed, and most of the light detected in the "off" state is actually scattered light from the in-plane laser(s). With output coupling into optical fibers, the contrast ratio is expected to be even higher.

The routing operation is demonstrated in Figure 7, in which side lasers 1 and 2 are each raised above threshold to suppress the stimulated emission in their associated VCSEL sections, while the other VCSEL remains on and routes the modulation signal out of the switch. The side laser input pulses have a negligible effect on the modulated outputs of the other VCSEL sections. Up to $\sim 2 \text{ mW}$ of VCSEL output could be suppressed in this way; if the VCSEL bias were higher, the stimulated emission was reduced by this amount, but not completely suppressed. There was incomplete electrical isolation between the individual laser sections, and this occasionally caused the VCSEL output to spike upward, e.g. as a forward bias was applied to an adjacent side in-plane control laser. However, as the gain quenching mechanism engages, and the VCSEL output drops rapidly as the side laser's output reaches steady state. This shows that the ultimate control of the output devices is in fact optical in nature, and the control signal can also be introduced into the side laser by optical injection.

Due to high series resistance and contact corrosion problems, the in-plane lasers (IPLs) lased at $\sim 350 \text{ A/cm}^2$ and 8 V , and the VCSEL sections at $\sim 2500 \text{ A/cm}^2$ and 10 V . The bit-transfer rate from the main laser to the VCSEL outputs was limited in this experiment by RC charging effects. The intrinsic speed of the intracavity-coupled lasers is expected to be sub-nsec range,

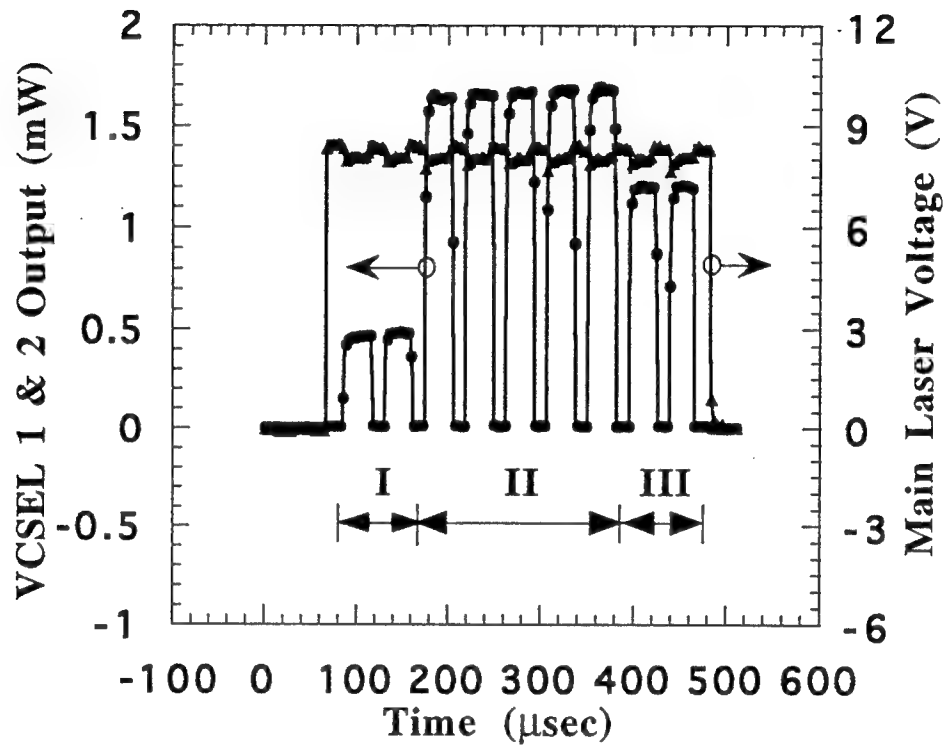


Fig. 6 Demonstration of the routing switch operation with the side control lasers off. The modulation signal on the main laser is amplified and inverted in the output of VCSELs 1 and 2, which are superimposed in region II due to their measurement with a 1 cm^2 Si photodetector. In regions I and III, the arbitrarily-chosen modulated output levels of VCSELs 1 and 2 are shown, respectively. The on/off contrast ratio is $>20 \text{ dB}$.

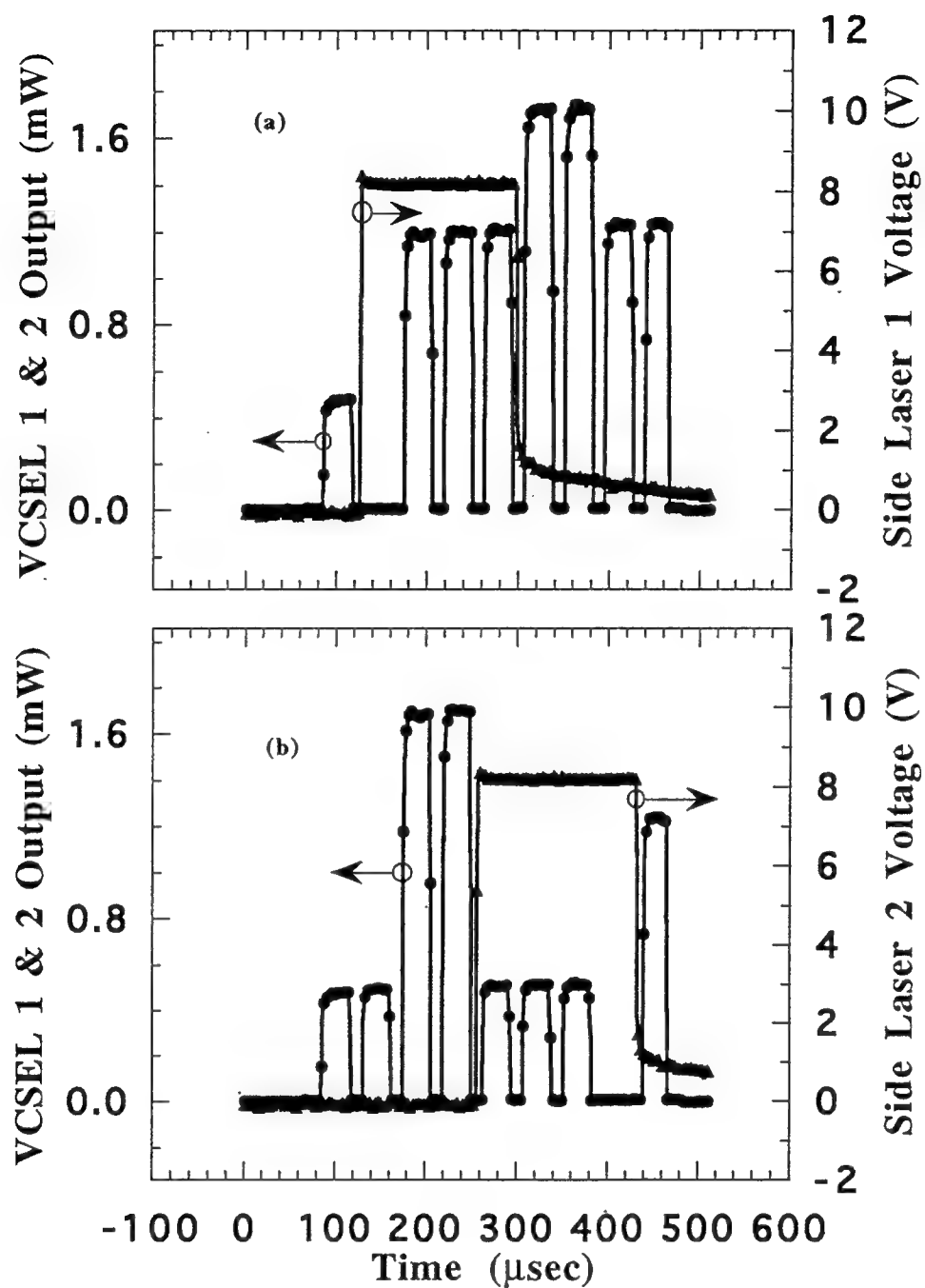


Fig. 7 (a) and (b) The side in-plane control lasers are used to switch off VCSELs 1 and 2 respectively, allowing the modulation signal from the main in-plane laser to be routed to the other VCSEL output. One VCSEL's side laser pulse has a negligible effect on the output of the other VCSEL.

since two-mode bistable device switching is limited only by the cavity lifetime, and not by the charge carrier lifetime as is the case in conventional semiconductor lasers [4],[5]. The switching speed of the VCSEL output control by the side lasers tested was also limited by processing problems and was in the range of 500 nsec. While operation at higher switching speeds was possible, the VCSEL output power did not achieve its maximum steady-state value before the in-plane modulation signal changed state, causing the VCSEL to be quenched once again. CW operation of the routing switch was measured in a cold probe station at -65 °C. While the measured switching speed is adequate for bit-rate transparent switching applications [12], improved processing and device design should allow for high-speed room-temperature operation in the near future.

As an output coupler for in-plane lasers, intracavity coupled VCSEL sections have several unique advantages. First, the large aperture leads to an easily collimated, low divergence output beam, which is well known. In addition, though, the modulation signal in the in-plane laser is coupled out through the shared laser population inversion with the VCSEL via the VCSEL's high reflectivity mirror. In this case, the main laser is not affected by coherent interference effects due to external optical feedback. This is significantly different from conventional partially reflecting output mirrors for in-plane lasers, which couple signals out directly through the electromagnetic field generated. Second, the amount of output coupling is separately optically or electrically controlled or switched. And finally, there can be multiple output coupling ports for the same main in-plane laser.

Other applications for these 1xN routing switches include basic logic gates and buffers in optical switching networks as well as time division multiplexing and demultiplexing operations. In the multiplexing case, the side in-plane control lasers would each have a modulation signal applied, for example through separately-biased in-plane cavity sections as mentioned above. With the VCSEL sections and the main in-plane laser biased near threshold, the input modulation signals would then be multiplexed in the main laser output. This signal could then be routed out of the wafer through a vertical cavity output coupler or to an adjacent device on the photonic integrated

circuit. For 2-D cascadability, coupled in-plane versions of similar devices must also be developed, and this work is currently underway [8], [9].

C. Conclusion

We have experimentally demonstrated for the first time the operation of a new, highly versatile monolithic semiconductor all-optical $1 \times N$ routing switch based on gain-quenched, intracavity-coupled semiconductor lasers. The intracavity VCSEL sections and the side control lasers to the main laser cavity also provide unique advantages for flexible output coupling of in-plane laser modulation signals. These devices will have a wide variety of time-division multiplexing and demultiplexing applications in addition to providing basic logic and buffer functions for optical network interconnections.

Conclusions and Future Work

We have successfully demonstrated optical bistability and memory in cross-coupled in-plane and vertical cavity lasers, and the conditions for the bistable behavior are now clearly established. Maximizing the overlap region between the two laser cavities is of primary importance, and it is expected that future work will lead to high-performance latching optical memory devices which are well-suited to routing and free-space transmission and optical input data. This was first demonstrated by fabrication of the all-optical two-input NOR gate described earlier, and later by the extension of the work to the fabrication of monolithic semiconductor 1:N routing switches. Additional work on improved device processing should allow for high-speed room-temperature operation of related all-optical switching devices in the near future, opening up new applications in the areas of basic logic gates and buffers in optical switching networks as well as in time division multiplexing and demultiplexing operations.

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